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Seasonal and topographic effects on estimating fire severity from Landsat TM/ETM+ data

David L. Verbyla[A,C], *Eric S. Kasischke*[B] *and Elizabeth E. Hoy*[B]

[A]Department of Forest Sciences, University of Alaska, Fairbanks, AK 99775, USA.
[B]Department of Geography, University of Maryland, 2181 LeFrak Hall, College Park, MD 20742, USA.
[C]Corresponding author. Email: d.verbyla@uaf.edu

Abstract. The maximum solar elevation is typically less than 50 degrees in the Alaskan boreal region and solar elevation varies substantially during the growing season. Because of the relatively low solar elevation at boreal latitudes, the effect of topography on spectral reflectance can influence fire severity indices derived from remotely sensed data. We used Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM) data to test the effect of changing solar elevation and topography on the Normalized Burn Ratio (NBR) and the differenced Normalized Burn Ratio (dNBR). When a time series of unburned pixels from black spruce forests was examined, we found that NBR values consistently decreased from June through September. At the stand level, dNBR-derived values from similar unburned and burned black spruce stands were substantially higher from September imagery relative to July or August imagery. Within the Boundary burn, we found mean post-fire NBR to consistently vary owing to topographic control of potential solar radiation. To minimise spectral response due to topographic control of vegetation and fire severity, we computed a dNBR using images from August and September immediately after a June–July wildfire. There was a negative bias in remotely sensed fire severity estimates as potential solar radiation decreased owing to topography. Thus fire severity would be underestimated for stands in valley bottoms dominated by topographic shading or on steep north-facing slopes oriented away from incoming solar radiation. This is especially important because highly flammable black spruce stands typically occur on such sites. We demonstrate the effect of changing pre- and post-fire image dates on fire severity estimates by using a fixed NBR threshold defining 'high severity'. The actual fire severity was constant, but owing to changes in phenology and solar elevation, 'high severity' pixels within a burn ranged from 56 to 76%. Because spectral reflectance values vary substantially as solar elevation and plant phenology change, the use of reflectance-based indices to assess trends in burn severity across regions or years may be especially difficult in high-latitude areas such as the Alaskan boreal forest.

Additional keywords: boreal forest, fire severity, Normalized Burn Ratio, solar elevation, topography.

Introduction

Fire severity has been estimated using a variety of remotely sensed indices (White *et al*. 1996; Patterson and Yool 1998; Isaev *et al*. 2002; Landmann 2003). The Normalized Burn Ratio (NBR) is a popular fire severity index applied by land management agencies in the western United States (Bobbe *et al*. 2001; Kotliar *et al*. 2003; Howard and Lacasse 2004; Key and Benson 2006; Miller and Thode 2007). This index responds to the substantial decrease in near-infrared reflectance (NIR, 0.76–0.96 μm for Landsat Thematic Mapper (TM)/Ehnanced Thematic Mapper Plus (ETM+) band 4) due to plant canopy damage and consumption by fire, and a substantial increase in shortwave infrared reflectance (SWIR, 2.08–2.34 μm for Landsat TM/ETM+ band 7) and is calculated using the following formula:

$$NBR = (NIR - SWIR)/(NIR + SWIR) \quad (1)$$

NBR can theoretically range from $+1.0$ to -1.0 and negative values are assumed to represent burned pixels, with fire severity increasing as NBR values become more negative.

To normalise for variations in pre-fire vegetation cover, and to avoid falsely mapping pre-fire unvegetated areas as 'high severity', a differenced NBR (dNBR) is sometimes used as:

$$dNBR = NBR\ pre\text{-}fire - NBR\ post\text{-}fire$$

dNBR can theoretically range from $+2.0$ to -2.0 and positive values are assumed to represent burned pixels, with fire severity increasing as dNBR values become more positive.

Van Wagtendonk *et al*. (2004) used Advanced Visible Infrared Imaging Spectrometer (AVIRIS) data to investigate the spectral responses of low, moderate and high severity classes in burned areas dominated by mature pines in California. They concluded that the two hyperspectral channels responding best to fire severity were spectrally similar to Landsat ETM+ sensor bandwidths, and supported the use of Landsat ETM+ NIR and SWIR bands to quantify burned areas and fire severity. Epting *et al*. (2005) examined 13 spectral indices in burned areas that contained a range of forest and shrub ecosystems in Alaska, and concluded that the NBR was an appropriate index of fire severity in forested areas. However, Roy *et al*. (2006) criticised the use of NBR and

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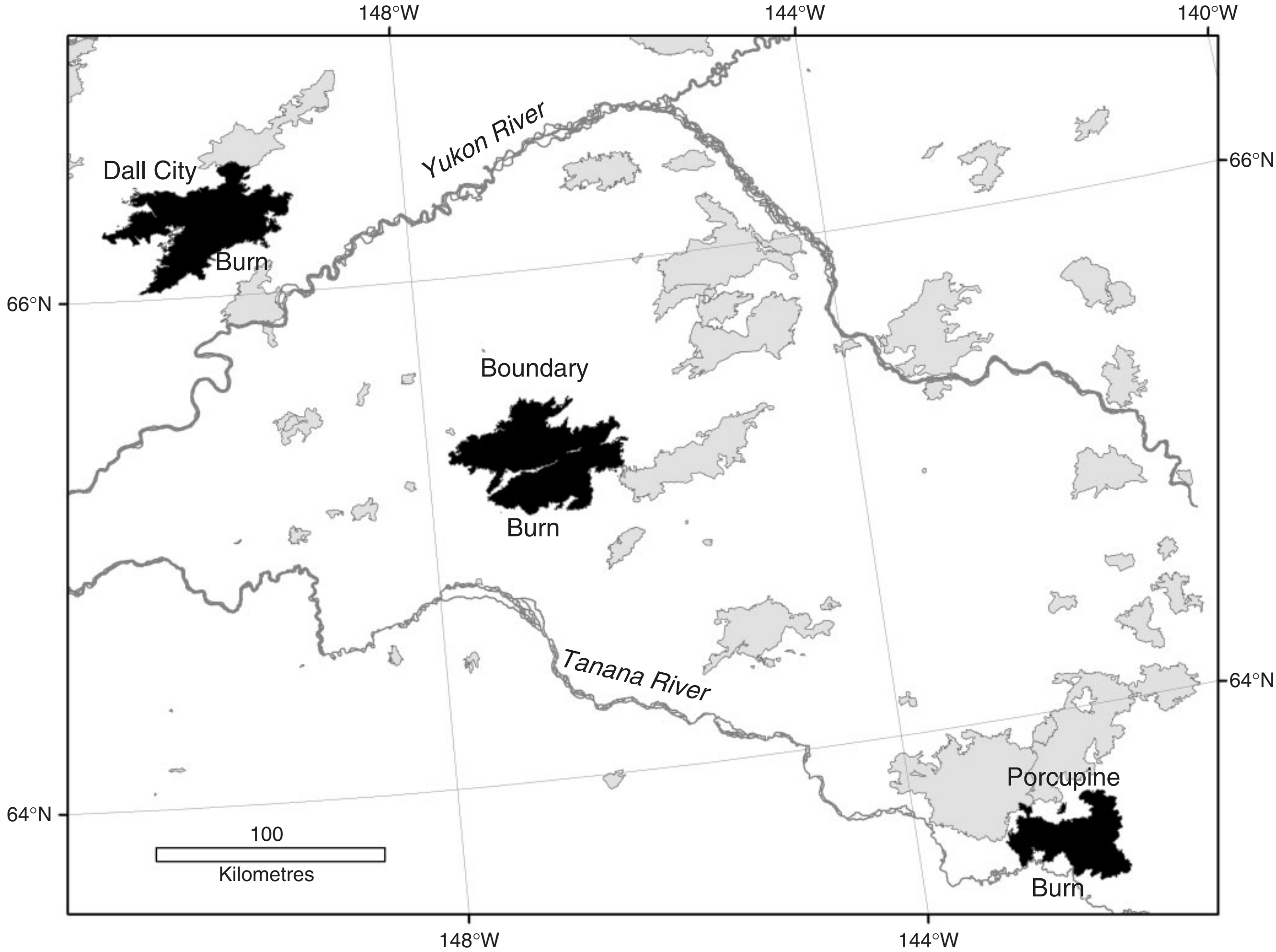

Fig. 1. Boundary, Dall City, and Porcupine burns. The other polygons represent burned areas from the 2004 fire season.

argued that NBR may not be an optimal index for evaluating fire severity as this index was originally designed to determine burned *v.* unburned areas and not to determine the severity of the fire.

The application of a ratio in creating remote-sensing indices has been recommended to reduce topographic effect on spectral response (Holben and Justice 1981; Short 1982; Key and Benson 2006). Based on this rationale, most studies using NBR have assumed the effect of topography on spectral response to be minor. Yet the effect of topography may be an important control on NBR in rugged mountainous areas, or at high latitudes where a low sun angle may enhance the topographic effect. For example, in the Alaskan boreal forest, solar elevations during the fire season are typically less than 50 degrees. Yet, to our knowledge no study has investigated the potential of topography as a confounding effect in the NBR spectral response independent of fire severity. The objective of the present study was to assess the potential impact of changing solar elevation and topographic effects on NBR spectral values.

Methods

Study area

The study areas included three burns from the summer of 2004: the Boundary burn, the Porcupine burn, and the Dall City burn (Fig. 1). These burns were from typical boreal landscapes with black spruce (*Picea mariana*) forest and woodlands dominating the cooler sites such as bottomlands and north-facing slopes, and aspen (*Populus tremuloides*) and birch (*Betula neoalaskana*) forests dominating warmer sites such as south-facing slopes at lower elevations. The Boundary and Porcupine burns fires started in mid-June, whereas the Dall City burn started in mid-July. The areas and sites used in our study burned before the end of August 2004 and all three fires were greater than 100 000 ha in size.

Field methods

Much of our field-based research in the 2004 fires focussed on mature black spruce stands, because these forest ecosystems are dominant across the landscape and typically comprise >70% of

Table 1. Mean Normalized Burn Ratio (NBR) within 1 to 10 km outside each burn perimeter

Image date	Sensor	Mean NBR	s.d. NBR	Solar elevation (degrees)	Solar azimuth (degrees)
Boundary burn unburned pixels					
18 June 2001 (pre-fire)	ETM+	0.503	0.102	47.33	164.34
18 July 2003 (pre-fire)	ETM+	0.476	0.188	44.36	159.06
4 August 2004 (post-fire)	ETM+	0.466	0.221	40.8	163.7
6 September 2004 (post-fire)	TM	0.398	0.213	30.0	166.1
Porcupine burn unburned pixels					
3 August 2002 (pre-fire)	ETM+	0.536	0.110	42.30	161.56
10 September 2001 (pre-fire)	ETM+	0.472	0.150	31.20	165.01
9 September 2004 (post-fire)	ETM+	0.420	0.111	30.25	166.37

the burned area. In particular, we were interested in evaluating the utility of the NBR or dNBR indices for estimating fire severity in terms of consumption of the deep (10 to >40 cm) surface organic layers that occur in mature Alaskan black spruce forests. As part of our studies, we not only collected data to calculate the composite burn index (which is a common metric used to assess the utility of the dNBR; Key and Benson 2006), but also collected other surface measures to assess fire severity (Kasischke *et al*. 2008).

For the current study, we selected black spruce stands that were located on opposing south and north aspect backslopes (slope position between shoulder and toe slopes) within the same watershed, each oriented in an east–west direction. The slope of each site was between 8 and 10%. One watershed was within the Boundary burn and contained Nome Creek, whereas the second was within the Porcupine burn with an unnamed creek. Data were collected in these watersheds to study the effects of topography on depth of burning and carbon consumption in the surface organic layers (Kane *et al*. 2007). In addition, we used data from the Dall City burn that were located on a flat (<2% slope) alluvial outwash.

We sampled several sites on each topographic position in the different burns, with the data collected including information on stand (overstorey tree) density, the level of consumption of the biomass in the crown layer, and depth of the surface organic layer, and measurements to estimate depth of the pre-fire organic layer (Kasischke *et al*. 2008). In addition, we collected the data necessary to compute the composite burn index (CBI) following Key and Benson (2006). For the present study, we used data from four south-aspect backslope and three north-aspect backslope sites in the Boundary burn, from five south-aspect backslope and three north-aspect backslope sites in the Porcupine burn, and from three flat sites in the Dall City burn.

Image processing

To investigate the effects of solar elevation angle on NBR, pre-fire and post-fire TM and ETM+ images were acquired for the Boundary and Porcupine study areas (Table 1). The 4 August 2004 imagery was also used to analyse the effects of variations in solar insolation class as a function of topographic position. End of growing-season images were acquired for both burns. In addition, we acquired pre-fire images from multiple dates in order to investigate the influences of variations in solar elevation angle.

To determine the spectral responses of our field sites, we used the following Landsat TM or ETM+ data. For the Boundary and Porcupine burns, we used the data from Hoy *et al*. (2008) (Boundary burn: pre-fire image collected on 18 July 2003; post-fire image collected on 4 August 2004; Porcupine burn: pre-fire image of 10 September 2001; post-fire image of 9 September 2004). For the Dall City fire, the best available pre-fire image was collected on 23 June 2001, whereas the post-fire image was collected on 3 September 2004. The large seasonal separation in time between the pre- and post-fire Landsat image collections is an unavoidable problem often encountered in Alaska.

NIR and SWIR reflectances were computed from each Landsat image using methods described in Chander and Markham (2003) and NASA Goddard Space Flight Center (2003). NBR was then computed from the band 4 and band 7 reflectances. Within each burn, we selected post-fire pixels with negative NBR values, which were assumed to be burned pixels (Trigg and Flasse 2000), and computed dNBR values for these pixels. In addition, for the Boundary and Porcupine burns, we selected pixels within a 1-km to 10-km buffer outside each fire perimeter as a representative sample of unburned pixels. The NBR of these pixels was then computed to determine whether there was a significant difference over time in mean NBR from unburned areas. Finally, for the five sites in Fig. 3, pixel spectral values for each site were determined using bilinear interpolation as suggested by Key and Benson (2006).

Modelling incoming solar radiation

If NBR was independent of topography, there would be no trend in NBR across the gradient of insolation classes within a burn. A digital elevation model of the Boundary burn was acquired from the US Geological Survey at a sample resolution of 2 seconds of latitude and longitude. The elevation samples were projected and resampled to a grid with 25-m cells in the Alaska Albers Equal Area map projection. A solar radiation model (Fu and Rich 2002) was used to simulate direct incoming solar radiation (insolation) at each grid cell, assuming an atmospheric transmittivity of 0.5. To test the effect of topography on NBR, we simulated insolation at the same time of satellite overpass for the 4 August 2004 Boundary burn image. We then aggregated pixels into 15 equal interval classes of insolation and then compared the mean NBR among insolation classes.

A trend of NBR across a gradient of insolation classes could be due to many factors associated with topography. Vegetation and therefore flammability varies with topography with relatively highly flammable black spruce forests and woodlands occurring on north-facing slopes and bottomlands, while lower-flammability vegetation such as aspen and birch typically occur at warmer, higher insolation sites.

By analysing the burned pixels from two post-fire images collected 1 month apart, factors that vary with topography such as vegetation and fire severity do not change substantially between the two image dates. We therefore created a dNBR (post-fire dNBR) image by subtracting burned pixels within the post-fire 4 August NBR image from the post-fire 6 September NBR image from the Boundary burn. As the area had burned by 4 August, the only major topographic factor that changed was sun elevation (40 *v.* 30 degrees). If NBR was independent of topography, the post-fire dNBR image would have values approximating a random normal distribution, centred at zero.

Results and discussion

Seasonal NBR changes in unburned pixels (1–10 km outside burn perimeters)

NBR computed from mean NIR and SWIR reflectances (Fig. 2) consistently decreased with decreasing solar elevation because the normalised difference between NIR and SWIR consistently decreased with decreasing solar elevation. When NBR was computed for each pixel, the mean NBR from unburned pixels also consistently decreased as solar elevation decreased (Table 1). When dNBR was computed for unburned pixels as August NBR minus September NBR, over 90% of the pixels had positive values and could be falsely interpreted as being burned. When dNBR was computed for unburned pixels as July NBR minus August NBR, 62% of the pixels had positive values. The reduction in NBR values from August to September was probably due to a combination of decreasing solar elevation angle and senescing broadleaf vegetation. Thus seasonal changes in NBR may result from a combination of changes in leaf area, vegetation senescence, and changes in solar elevation.

The decrease in NBR from July to August to September may add significant noise to fire severity estimates from dNBR. Ideally the pre-fire and post-fire images should be from the same solar day of the year to minimise the effect of solar elevation on spectral response. However, this requirement is often difficult to achieve in Alaska where cloud cover is a common problem during the growing season, especially in August and September when precipitation is greater than earlier in the growing season. In addition, for analysis of historical fires using Landsat TM imagery from the early to mid-1990s, availability of data is limited because of the failure of the tape recorder onboard Landsat 5.

Because of the relatively low solar elevation at high latitudes, cloud shadows can also affect image quality. For example, a post-fire image from late August or early September with 10% cloud cover may have more than 25% pixels of poor spectral quality due to clouds and associated cloud shadows. Even if cloud-free pre-fire and post-fire images were available from the same solar day of the year, plant phenological differences are likely

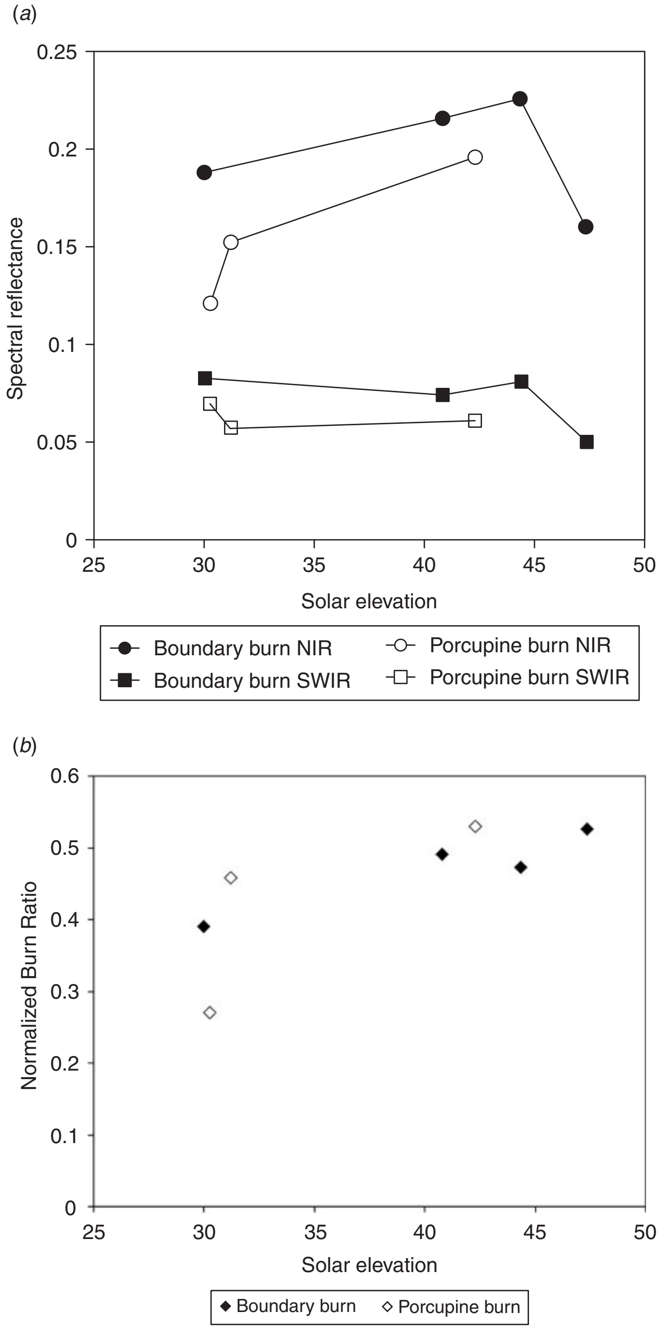

Fig. 2. (*a*) Mean Near Infrared (NIR), Shortwave Infrared (SWIR) reflectances from unburned regions (1–10 km outside each burn perimeter) of the Boundary and Porcupine burns. The date with the highest solar elevation (47°) was 18 June, which is early in the growing season. (*b*) NBR values computed using the mean NIR, SWIR reflectances from Fig. 2*a*.

because of interannual variations in precipitation and temperature. For example, the precipitation in Fairbanks for June through August was 215 mm in 2003 and only 46 mm in 2004 (Alaska Climate Data Center, http://climate.gi.alaska.edu/, accessed 22 July 2008). Kasischke and French (1997) noted a 15–25% variation in mid-season Normalized Difference Vegetation Index

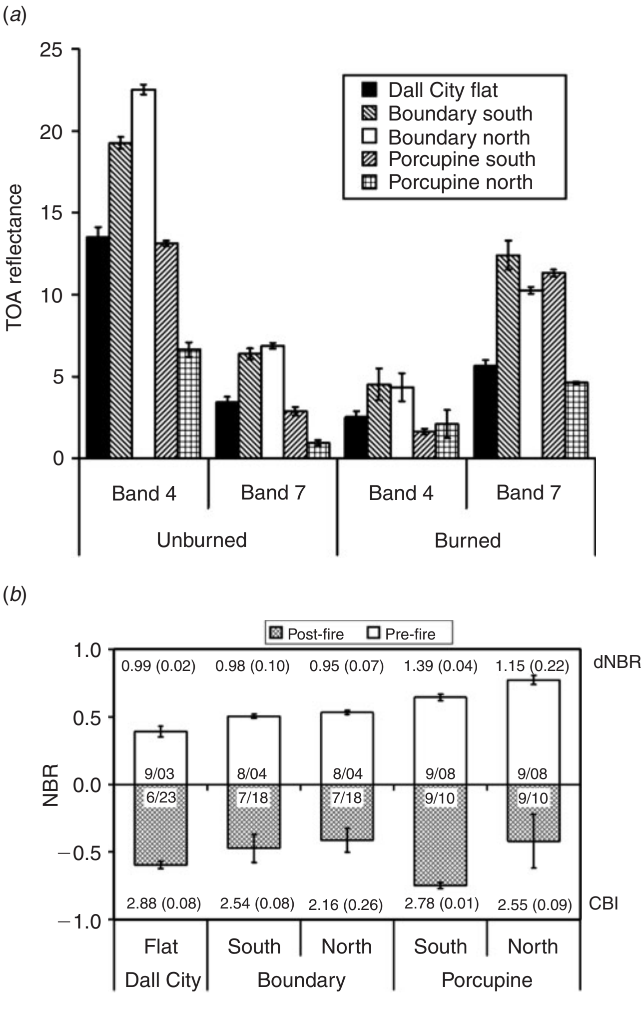

Fig. 3. The impacts of combined effects of slope, aspect, and solar elevation on (*a*) surface reflectances (top of atmosphere reflectance, TOA) in Landsat Thematic Mapper (TM) and Ehanced Thematic Mapper (ETM+) bands 4 and 7; and (*b*) Normalized Burn Ratio (NBR) and composite burn index (CBI). The error bars are in standard errors. In (*b*), we present average (standard error) CBI and dNBR as well. The numbers within the bar charts represent the month and day of the collection of the Landsat TM/ETM+ imagery.

(NDVI) from different forest types in 2 consecutive years in interior Alaska due to variations in precipitation.

Stand-level spectral responses: north- v. *south-facing slopes* v. *flat topography*

Overall, the spectral reflectances from the unburned stands on different topographic positions in the three burns behaved according to the patterns observed in Fig. 2, with reflectance in bands 7 (SWIR) and 4 (NIR) being the highest for the Boundary burn sites (collected on 18 July at a 44° solar elevation), followed by the Dall City burn sites (collected on 23 June at ∼47° solar elevation), and the Porcupine burn sites (collected on 10 September with a 31° solar elevation) (Fig. 3*a*). The same general trends were noted in the band 4 and 7 reflectances from the burned stands. There were differences in reflection between stands collected on north- and south-aspect slopes. The reflectances were higher in the north-aspect unburned sites in the Boundary burn for band 4, but higher for the south-aspect sites in the Porcupine burn in both bands 4 and 7. For the burned stands in both the Boundary and Porcupine fires, the band 7 reflectance was higher in the south sites; however, caution should be used in interpreting variations in reflectance in burned stands because fire severity varies as a function of aspect (Kane *et al*. 2007).

The net effect of variations in solar elevation, topography, and fire severity on NBR and dNBR for the topographic study sites is illustrated in Fig. 3*b*. Variations in NBR for the unburned sites follow the trends given in Table 1, although the differences are not as great. An apparent topographic effect is that north-slope sites have a lower pre-fire NBR than south-slope sites, particularly in the Porcupine sites. In terms of impacts of fire severity as measured by CBI, for the Landsat data collected in early September, we expected the flat Dall City burn sites would have the highest NBR and the north-facing to have the lowest. In fact, the opposite trend was observed (Fig. 3*b*). The same trend was observed for the Boundary burn in that the north-slope sites had a higher than expected NBR based on their lower CBI value.

As a result of the interactions between the effects of topography and solar elevation on NBR in burned and unburned stands, the variations in dNBR are extremely complex for the five topographic positions examined in our study, the end result being that there were low correlations between dNBR and CBI for the black spruce stands sampled in the 2004 fires (Hoy *et al*. 2008).

NBR trends across a solar radiation gradient within the Boundary burn

There was a consistent decreasing trend in mean post-fire NBR as insolation class varied from lowest insolation class to the class corresponding to a level surface (Fig. 4*a*). At insolation classes greater than at a level surface, the mean NBR trend continued to decline, except for an abrupt recovery to the level surface value at the highest insolation class. Because a more negative NBR is assumed to represent a higher fire severity, this trend is opposite to that expected because highly flammable black spruce typically occurs on lower-insolation sites, whereas less flammable aspen and birch stands typically occur on higher-insolation sites. By examining the components of NBR, NIR and SWIR reflectance, it is clear that the NIR and SWIR spectral responses represent different non-linear functions in relation to insolation class (Fig. 4*b*).

By creating a post-fire dNBR image from two post-fire images, spectral response due to topographic effects other than change in sun elevation, such as varying vegetation and fire severity, are minimised. Fire severity is assumed to increase with more positive dNBR values. In the present case, the post-fire dNBR values were biased with 42% of the area having post-fire dNBR values less than −0.05 and only 13% of the area having post-fire dNBR values greater than +0.05 (Fig. 5*a*). The negative bias increased as insolation class decreased (Fig. 5*b*). Thus fire severity would be underestimated for stands in valley bottoms dominated by topographic shading or on steep north-facing slopes oriented away from incoming solar radiation. This is especially important as highly flammable black spruce stands typically occur on such sites. Within the study area, 22% of the pixels had a post-fire dNBR less than −0.10; thus the

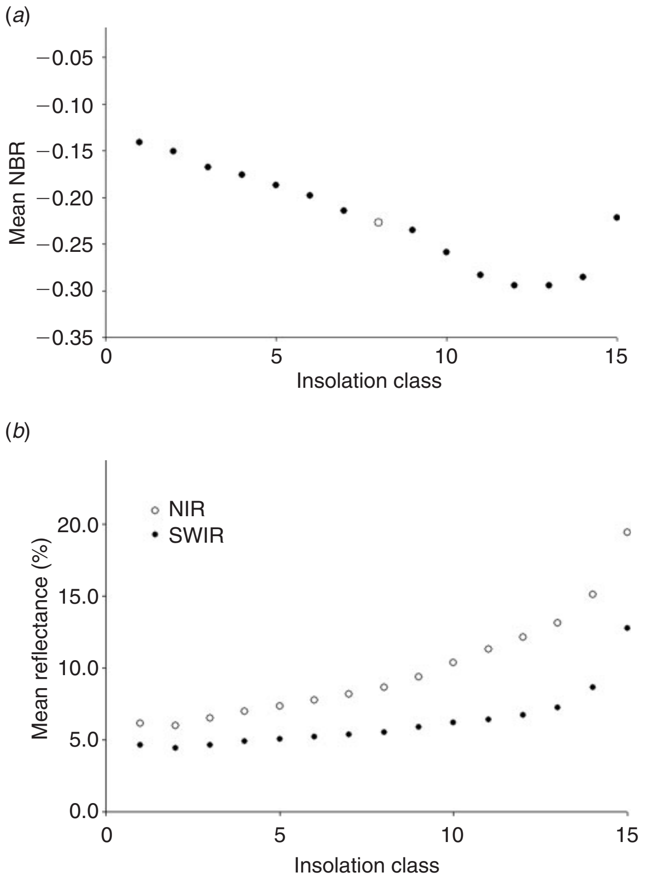

Fig. 4. (*a*) Mean post-fire NBR within the Boundary burn by insolation class for 4 August 2004. A level surface would belong to insolation class 8 (symbolised by the open circle). Insolation classes correspond to $W\,m^{-2}$ at the time of satellite overpass (1, $<1\,W\,m^{-2}$; 2, $1–2\,W\,m^{-2}$; ... 14, $14–15\,W\,m^{-2}$; 15, $>15\,W\,m^{-2}$). (*b*) Non-linear response of mean NIR and SWIR reflectances as a function of insolation class.

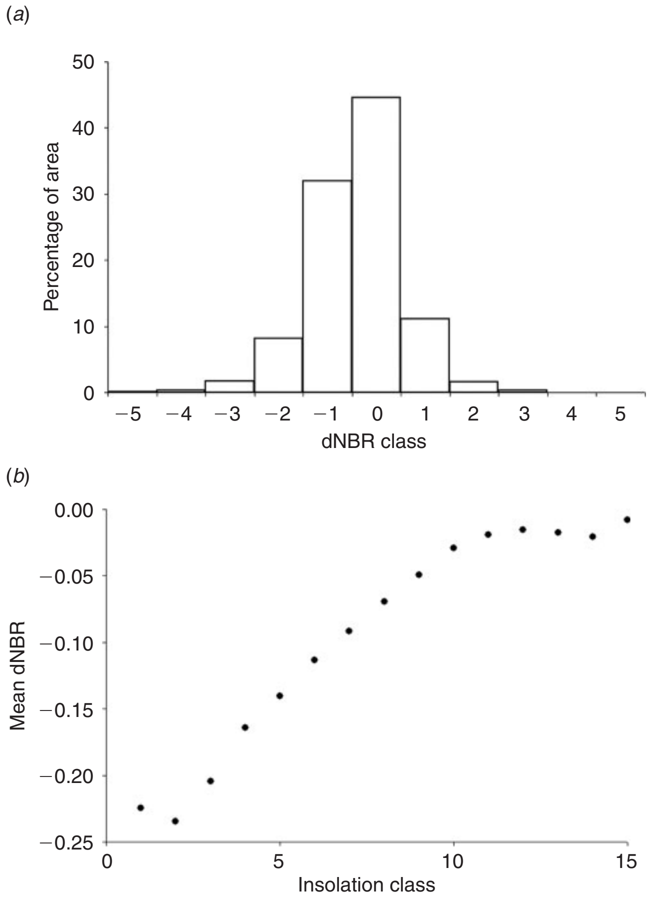

Fig. 5. (*a*) Histogram of post-fire differenced Normalized Burn Ratio (dNBR) values (4 August–6 September 2004). Each class has a width of 0.1 dNBR units, with class 0 ranging from −0.05 to +0.05, class 1 ranging from 0.5 to 1.5, class −1 ranging from −0.1.5 to −0.5, etc. (*b*) Mean post-fire dNBR (4 August–6 September 2004) by insolation for 4 August 2004. Insolation classes correspond to $W\,m^{-2}$ at the time of satellite overpass (1, $<1\,W\,m^{-2}$; 2, $1–2\,W\,m^{-2}$; ... 14, $14–15\,W\,m^{-2}$; 15, $>15\,W\,m^{-2}$).

Table 2. Mean differenced Normalized Burn Ratio (dNBR) (based on 1 230 939 pixels) within Boundary burn by image date

Pre-fire image date	Post-fire image date	Mean dNBR	s.d.
18 June 2001	4 August 2004	0.743	0.143
18 July 2003	4 August 2004	0.797	0.157
18 June 2001	6 September 2004	0.702	0.168
18 July 2003	6 September 2004	0.756	0.180

topographic effect can be an important source in controlling post-fire NBR values independent of fire severity in regions of steep topography or relatively low sun elevations.

There are several approaches that may reduce the topographic effect on fire severity estimates. One approach is to normalise spectral reflectance by modelling illumination conditions using a digital elevation model (Civco 1989; Ekstrand 1996; Riano *et al*. 2003). An alternative approach would be to stratify burned areas by pre-fire vegetation type and topographic position and to develop fire severity estimates from remotely sensed data within each stratum.

False trends in dNBR

The mean dNBR for the burned pixels within the Boundary burn was significantly different depending on the pre-fire or post-fire image used (Table 2). A later pre-fire image consistently resulted in a higher mean dNBR within the burn (Table 2).

If we assumed the dNBR fire severity thresholds of Epting *et al*. (2005), fire severity classes would vary substantially, depending on the timing of pre- and post-fire images (Fig. 6). Therefore we advise caution in the use of dNBR or any remotely sensed reflectance-based index that is sensitive to solar elevation and plant phenology to monitor trends in fire severity either in time or across regions. There should be fire severity field data to assess the appropriate remotely sensed threshold value that really corresponds to severity levels estimated from remote sensing.

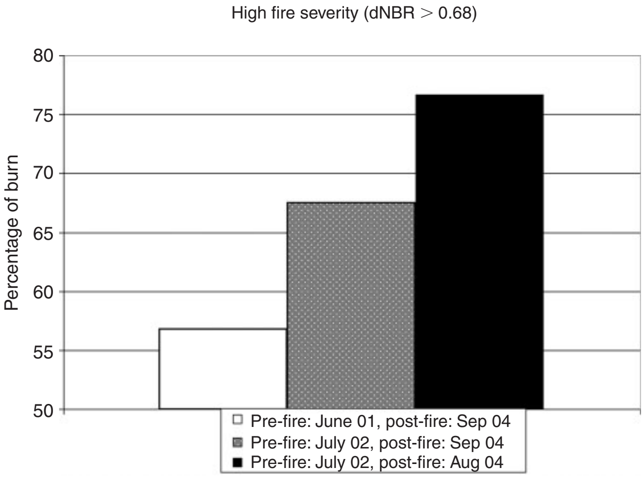

Fig. 6. Artificial increase in 'high severity' pixels within the 2004 Boundary burn due to change in image acquisition dates.

Conclusions

Topographic shading could substantially reduce fire severity estimates from NBR in valley bottoms and steep north-facing slopes. This bias is important in boreal forests in Alaska because these sites are typically dominated by highly flammable black spruce. Accurate mapping of fire severity in black spruce is important in a variety of applications such as estimating carbon emissions due to wildfire, predicting post-fire vegetation succession and flammability as a function of vegetation type, and mapping of future wildlife habitat.

NBR values can change independently of fire severity at the stand scale owing to slope orientation, at the burn level owing to topographic effects across the landscape, and across images taken from different months. The use of NBR or dNBR to assess fire severity trends across regions or years may be difficult because changes in solar elevation and associated topographic effects, as well as plant phenology changes may substantially influence remotely sensed spectral indices and associated estimates of fire severity. Fire severity data from a representative sample of vegetation and topographic classes would be needed to calibrate and validate remotely sensed estimates.

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